THE INFLUENCE OF ACCOMMODATION AND CONVERGENCE UPON THE PERCEPTION OF DEPTH.

By J. W. BAIRD, B. A., Ph. D.

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The present study is an attempt at the settlement of a much-disputed question: the question as to what part the mechanisms of accommodation and convergence play in our visual perception of the third dimension. For many years past, psychological opinion as to this point has been sharply divided; and the experimental data hitherto available are inadequate to a final decision of the question. The evidence adduced in the following pages points unmistakably to some such theory of visual space perception as is advocated by Wundt. A theory of space perception at large must of course be confirmed along many converging lines; and the present investigation is concerned only with a single partial problem. So far as they go, however, our results speak unequivocally for the influence of movement factors upon the visual perception of depth.

The writer's attention was first directed to the general problem of visual space perception in 1899, when he was a student of psychology in the University of Wisconsin. From 1899 to 1901 he was engaged, though with frequent interruptions,

upon a review of the literature of psychological space. Experiments upon the special problem of this paper were carried out in the Cornell Psychological Laboratory during the academic year 1902-3.

The study falls naturally, therefore, into two parts; an historical survey of the course of development of psychological doctrine regarding the visual perception of the third dimension,[1] and an account of the experimental work upon which our own conclusions are based.

I. Historical.

Attempts were made as early as the fifteenth century to determine the factors contributing to the perception of depth. Da Vinci[2] in his Treatise on Painting described various devices employed by painters for the production of the illusion of relievo and distance. It is impossible to determine who first advanced the theory that the adjustment of the ocular mechanisms, in convergence and accommodation, furnishes a criterion of distance. It is evident, however, that this theory had been advocated as early as the beginning of the seventeenth century. Aguilonius[3] mentions the theory as current in his day and attempts to refute it. In the opinion of Descartes[4] both the accommodation of the refractive media of the eye, and the convergence of the visual axes contribute to the perception of distance. "The perception of distance . . . . depends primarily upon the form of the eyeball, for its form when we see a near object must be slightly different from its form when we see a more distant object. And, according as we bring about in the form of the eyeball a change which is appropriate to the distance of the object seen, we also change

[1] Much of the literature quoted below has important bearings upon the question of space perception in general. It has been our aim, however, to draw upon it only in so far as it has reference to our special problem. We hope that the reader will overlook what might otherwise seem to be serious omissions in our historical sketch.

[2] Leonardo da Vinci: 1452-1519, *Trattato della Pittura*, English translation, *Treatise on Painting*, by J. F. Rigaud. New Ed., 1877. § § 117, 121, 124, 178, 187, 191, 199, 204-211, 283-324, 340-344, 348. It is interesting to note that, although da Vinci's analysis of the perception is far from being complete and exhaustive in the light of modern science, he yet enumerates and describes practically all of the factors employed even by the modern painter. It is a fact of interest, too, that da Vinci called attention to the influence of binocular vision upon the perception of depth. He just missed stating the principle of disparity of retinal images which Wheatstone discovered more than three hundred years later. *Treatise on Painting*, § 124; Charles Wheatstone, *Philosophical Transactions*, 1838. pp. 371-394.

[3] Francisci Aguilonii: *Opticorum libri sex*. Antwerp, 1613. Lib. III. Prop. III.

[4] Cartesius: *Dioptrice*. 1637. VI, 11 and 13.

a certain part of our brain in such manner as is instituted by nature to make the mind perceive that distance. . . . . Secondly we perceive distance by the relation which the two eyes bear to each other. For consider a blind man, who holds in his hands two converging staffs. Their length he does not know, but knows only the distance between his hands, and the magnitude of the angles which the converging staffs make with an imaginary line joining his two hands. He perceives by a sort of natural geometry (*ex geometria quadam omnibus innata*) the distance of the point of intersection of the staffs. So we, when our eyes are converged upon a point, know the distance of that point by the length of the interocular line and the magnitude of the angles formed at the points of intersection of the interocular line and the visual axes."[1]

Descartes' theory of the part played by accommodation lapsed with the lapse of the theory of the mechanism of accommodation which it assumed,—although it is not different in principle from the view dominant in the psychology of a few decades ago. His explanation of the function of convergence was rejected by Berkeley who pointed out[2] that as a matter of fact we possess no knowledge of the oculo-geometrical relations whose assumption furnished the basis of the Cartesian account.

Malebranche[3] enumerates six "signs of distance." The first and second of these are, however, nothing more than Descartes' accommodation and convergence criteria, and the other four do not concern us here. Molyneux[4] defends the Cartesian theory against the attacks of opponents and brings forward another criterion of distance which has, however, never found favor. He is of opinion that "when we estimate the distance of nigh objects, either we take the help of both eyes, or else we consider the pupil of one eye as having breadth, and receiving a parcel of rays from each radiating point. And, according to the various inclinations of the rays from one point, on the various parts of the pupil, we make our estimate of the distance of the object."[5]

Berkeley[6] set himself the task of showing "the manner in which we perceive by sight the distance . . . . . of objects. . . . . . It is, I think, agreed by all that distance of itself, and immediately, cannot be seen. For distance being a line directed endwise to the eye, it projects only one point in

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[1] Cartesius: *Ibid.* VI, 11, 13. Paraphrase.
[2] G. Berkeley: *An Essay towards a New Theory of Vision*, 1709, § § 4, 8-17.
[3] N. Malebranche: *Recherche de la Vérité*, 1675, I. 9.
[4] Wm. Molyneux: *A Treatise on Dioptrics*. Dublin, 1690.
[5] *Ibid.* Part I.
[6] *Op. cit.*, § § 1 and 2.

the fund of the eye—which point remains invariably the same, whether the distance be longer or shorter." He refutes the contentions of Descartes and of Molyneux[1] and maintains that accommodation and convergence furnish a threefold "sign" of the distance of near objects. "First, it is certain by experience, that when we look at a near object with both eyes, according as it approaches or recedes from us, we alter the disposition of our eyes by lessening or widening the interval between the pupils. This disposition or turn of the eyes is attended with a sensation, which seems to me to be that which in this case brings the idea of greater or lesser distance into the mind. . . . . . Secondly, an object placed at a certain distance from the eye, to which the breadth of the pupil bears a considerable proportion, being made to approach, is seen more confusedly. And the nearer it is brought the more confused appearance it makes. And, this being found constantly to be so, there arises in the mind an habitual connection between the several degrees of confusion and distance; the greater confusion still implying the lesser distance and the lesser confusion the greater distance of the object. . . . . . Thirdly, an object being placed at the distance above specified, and brought nearer to the eye, we may nevertheless prevent, at least for some time, the appearance's growing more confused, by straining the eye. In which case that sensation supplies the place of confused vision, in aiding the mind to judge of the distance of the object; it being esteemed so much the nearer by how much the effort or straining of the eye in order to distinct vision is greater."[2]

Berkeley's Essay was followed by a voluminous criticism—favorable and adverse; but little positive advance was made until the beginning of the last century. Berkeley's theory was opposed by R. Smith,[3] Condillac,[4] Wm. Porterfield[5] and others, but was supported by Condillac,[6] Voltaire,[7] D. Hartley,[8] T. Reid,[9] Adam Smith,[10] Dugald Stewart,[11] Thomas Brown,[12] Sir Wm. Hamilton,[13] A. Bain,[14] John Stuart Mill,[15] and J. Mackintosh.[16]

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[1] *Ibid.*, § § 4-15 and *Appendix to Second Edition.*
[2] *Ibid.*, § § 16-27.
[3] *A Complete System of Opticks*, Cambridge, 1738.
[4] Essais sur l'origine des connaissances humaines, 1746, I.
[5] *A Treatise on the Eye, the Manner and Phenomena of Vision*, 1759.
[6] *Traité des Sensations*, 1754. Condillac was at first opposed to the Berkeleian theory of vision but later accepted it.
[7] *Élémens de la philosophie de Newton*, 1738.
[8] *Observations on Man*, 1749.
[9] *Inquiry into the Human Mind*, 1763.
[10] *Essays. On the External Senses*, 1795.
[11] *Elements of the Philosophy of the Human Mind*, 1792.
[12] *Lectures*, 1811.
[13] *Lectures on Metaphysics*, 1837; *Reid's Works*, 1847.
[14] *Senses and Intellect*, 1855.
[15] *Discussion*, 1859. [16] *Dissertations*, 1862.

The Berkeleian principle, in so far at least as it concerned convergence, was taken up and extended by Steinbuch in Germany.[1] Steinbuch asserted, of all three dimensions of space, what Berkeley had posited for depth alone,—that their perception is a result of the sensations aroused by the contraction of the ocular muscles. When an object makes its appearance in the field of vision, we run our eyes over its various dimensions; and the amount of spatial extension which we ascribe to it is determined by our consciousness of the amount of muscular contraction employed in successively regarding its several parts.

A novel explanation of the *modus operandi* of depth vision was brought forward by Lehot.[2] In the opinion of Lehot the retinal image of a solid object itself possesses tridimensionality. This corporeal image, standing upon the retina, projects into the substance of the vitreous humor, and is there sensed as tridimensional by means of the sensitive fibres with which that humor is supplied.

Hueck[3] was the first investigator to attack the problem experimentally. He performed a series of experiments which he thought established the fact that ocular movements of convergence influence our judgment of the position and distance of the objects fixated. Besides establishing this relation for the normal eye, Hueck maintained that certain abnormal phenomena in space localization were explicable from the pathological condition of the ocular muscles. A few years later, Meyer[4] described experiments which seemed to prove that consciousness of change of convergence of the visual axes gives rise to a change in our estimation of the magnitude and distance of visual objects. Meyer's experiments consisted in a successive fixation of points before and behind a surface upon which was printed a series of congruent figures—wall-paper patterns. He found that with near fixation, or increased convergence, the figures appeared to be small and near, while with decreased convergence they seemed to be larger and more remote. In a later and more detailed investigation, Meyer[5]

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[1] *Beiträge zur Physiologie der Sinne*. Nürnberg, 1811.

[2] C. J. Lehot: *Nouvelle théorie de la vision*. Paris, 1823. This is the earliest record we have been able to find of an attempt to explain depth-vision from a purely Nativistic standpoint. Lehot's treatise antedates the work of Johannes Müller—the reputed founder of Nativism—by several years. Moreover Müller's *Vergleichende Physiologie* is, after all, only the modest beginning of a very modest Nativistic theory. It contains no more than the germ of the radical Nativism of his successors.

[3] Alex. Hueck: *Die Achsendrehung des Auges*, Dorpat, 1838.

[4] Hermann Meyer: *Ueber einige Täuschungen in der Entfernung*. *Archiv für physiologische Heilkunde*, 1842.

[5] Hermann Meyer: *Ueber die Schätzung der Grösse und Entfernung*. *Poggendorff's Annalen der Physik und Chemie*. III, *Reihe*. XXV, 1852. 198-207.

employed a modified form of the Wheatstone stereoscope. He found that, if two figures were inserted in the slides and combined into a single image, this stereoscopic image appeared to approach and recede from the observer, in the direction of depth, according as the figures were moved back and forth in the slides. He showed by means of a drawing, representing the paths of the reflected rays, that the change of apparent distance corresponded throughout the series with the change of convergence of the visual axes. That is, if with any given position of the figures in the slides, the eyes were required to assume a position of greater convergence in order to combine the images, the single image was projected to a near distance, while, on the other hand, if a farther point must be fixated in order to bring about the blending of the images, the visual object was localized at a greater distance from the eye.

In 1852 Lotze brought forward his well-known theory of "Local Signs."[1] When an object makes its appearance in the field of vision the eyes reflexly turn in such a manner as to bring the images of the object to the part of clearest vision. The ocular movement necessary for the transference of the image from any lateral point to the fovea differs in magnitude and direction for every lateral retinal point. If now these movements are attended by muscular sensations, and if the latter constitute a series of sufficiently fine gradation, every retinal point will furnish in the peculiar movement which corresponds to it and to it alone, a clue for the localization of its objective stimulus. Nor are actual movements necessary, in the opinion of Lotze; the mere tendency to movement may suffice to bring to consciousness a reproduced sensation corresponding to the appropriate movement, and may thereby furnish the local sign.

The Lotzian doctrine was worked out in detail by Meissner.[2] Meissner assumes that every visual sensation has a breadth, height and depth-value, which are referred to a system of ordinates passing through the point of fixation in external space. The point at which the visual axes intersect the center of this system of ordinates is seen to be the center of the binocular field of vision. This point is the point of reference of the space system; the spatial relations of all other parts of the visual field are evaluated in terms of their distance and direction from this zero-point. The localization of any lateral stimulus in relation to this central point is brought about by the sensation of movement which accompanies the transference of the image to the fovea. Breadth and height-values are furnished in monocular vision; depth-values come to consciousness only in binocular vision.

[1] H. Lotze: *Medicinische Psychologie*, 1852.
[2] Georg Meissner: *Beiträge zur Physiologie des Sehorgans*, 1854.

In the course of its development since the days of Descartes and Berkeley, this Empiristic Theory, as it is called, had not only been filled out in detail; it had been enormously broadened in scope as well. Berkeley had made the perception of depth a function of muscular sensations. The later and more extreme Empirists assert that all space perception—breadth and height as well as depth—is dependent upon sensations arising from eye-movements. Berkeley had further maintained that the relation between a given visual sign and the distance which it signifies is purely arbitrary, and that this relation is discoverable only by experience. That this principle can be posited of breadth and height in the same sense in which Berkeley held it to be true of depth, can scarcely be maintained. It is unfortunate that many Empirists have evaded this issue.

The Empiristic theory did not long remain in undisputed possession of the field. Beginning, as is commonly supposed, with Johannes Müller, there arose the rival theory of Nativism, whose development we must now trace. The terms Empirism and Nativism are unhappily chosen. Neither the Nativist nor the Empirist would subscribe to a rigid formulation of any such doctrine as his title implies. For the latter is as far from holding that our earliest experience is absolutely non-spatial in character as is the former from believing that our adult spatial vision is a connate endowment.

Johannes Müller[1] combats the view advanced by Steinbuch, objecting that the latter's argument is unsound, in that he derives space perception from a consciousness of movements which itself presupposes the idea of space. Müller, on the contrary, believes that the capacity to see space is an innate endowment of the retina. Even when the eyes are closed and unmoved, the retina "sees itself extended." Yet Müller believes that eye movements are an important secondary factor in the development of our adult perception of space.

A new impulse was given to the Nativistic theory by Dove's refutation of Brücke's view. A few years previously, Wheatstone's[2] earliest stereoscopic experiments had convinced their author of the erroneousness of the theory of identical retinal points. It had long been held that the explanation of the circumstance that though we see with two eyes yet we are conscious of but a single image, was to be found in the fact of the paired arrangement of retinal points. Every point on the one retina has its mate on the other; and it is characteristic of

[1] Johannes Müller: *Vergleichende Physiologie des Gesichtsinnes*, 1826, pp. 52 ff.

[2] Charles Wheatstone: *Contributions to the Physiology of Vision*, Philosophical Transactions, 1838, pp. 371-394.

these identical points, that the simultaneous stimulation of any pair gives rise to an unitary perception. Wheatstone, however, found an essential condition of stereoscopic vision in the disparity of retinal images. Since it is impossible that two dissimilar projections of an object can be imaged at the same time upon similar or identical parts of the two retinas, and since, moreover, two dissimilar projections may give rise to a single image of the object, Wheatstone felt himself obliged to reject the theory of identity. But he was also obliged to rest content with this half-way measure; for he was unable to advance a satisfactory hypothesis to replace the old. Brücke,[1] doubtless at the instigation of the horopter discussions in the literature of that period, found a solution of the problem which at once saved the theory of identity and explained the phenomena of stereoscopic vision. Since only those points which lie upon the momentary horopter can at any one instant be seen singly and clearly, Brücke finds it necessary to assume that the normal procedure in seeing a solid object consists essentially in a rapid series of eye-movements, during the course of which the various parts of the object are successively fixated. By this means, the parts are successively imaged upon identical retinal points; and meanwhile the different distances of the parts, *i e.*, the tridimensionality of the object, is perceived from the sensations aroused by the movements of convergence. When we regard stereoscopic pictures, a similar series of eye-movements exposes identical points on the two retinas to the various parts of the object fixated, and the consequent perception of relief is, here too, to be explained from sensations of convergence.

Dove[2] showed that it is possible to get the stereoscopic effect with an instantaneous exposure of the stereograms.[3] Since his exposure was computed to have a duration of less than the ten millionth part of a second, we are left to conclude, either that the eye-movements occur with inconceivable rapidity or that they are not an essential condition of stereoscopic vision. It is a surprising fact that notwithstanding Dove's demonstration, Brücke's theory was still accepted without question by several subsequent writers, *e. g.*, Prevost, Brewster and Abbott.

Panum, however,[4] saw in Dove's demonstration a telling

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[1] Ernst Brücke: *Ueber die stereoskopischen Erscheinungen u. s. w. Müller's Archiv f. Anatomie*, 1841, p. 459.

[2] H. A. Dove: *Berichte d. Berliner Akademie*, 1841, p. 252.

[3] This demonstration has since been repeated in various forms by Volkmann, Panum, Donders, Aubert and others. The most familiar modern form is that described by Hering in connection with his falling ball apparatus. *Arch. f. Anat., Physiol. u. wiss. Med., Leipzig*, 1865, p. 512.

[4] P. L. Panum: *Physiologische Untersuchungen über das Sehen mit zwei Augen*, 1858. The writer has been unable to gain access to a

argument against the Empiristic doctrine of psychological space. The theory which he advocates is a Nativism of the most pronounced type. It is true that Johannes Müller had made spatial vision an innate capacity of the retina; but Müller had brought forward only a skeleton theory, and had but vaguely indicated the course of the ontogenetic development of visual space perception which he advocated: Panum attacked the problem more resolutely, and if he did not find a satisfactory solution, at least made a valuable contribution to the literature, and directed the discussion into a path which led his successors to fruitful results. If, as Dove's experiment seemed to show, sensations of movement are a non-essential in spatial vision, it is only natural that Panum should seek to find, in the retina itself, the conditions which are necessary. Accordingly Panum was led back to Müller's hypothesis and himself maintained that visual space is a function solely of the retina and its central nervous mechanism. For Panum the spatial position of a visual object is given us immediately in sensation. This specific sensation of space is conditioned by the position of the image upon the retina. The sensation of depth, which is a product of the simultaneous co-operation of the two retinas he calls "the sensation of binocular parallax." If, now, a characteristic space sensation corresponding to each individual retinal point is aroused simultaneously with the stimulation of that point, and if, moreover, this space-sensation suffices for the localization of the visual sensation at a point in space coincident in all three dimensions with the position of the stimulus, we have a simple and satisfactory solution of the problem. Eye-movements and eye-movement sensations alike become unnecessary and superfluous. But if we ask just what constitutes the differentiation between the several space-sensations belonging to the various retinal points, *i. e.*, if we seek for criteria which may take the place of Lotze's movements and movement tendencies or Steinbuch's "muscle-ideas" in rendering the whole procedure possible or comprehensible, we find that Nativism, even in the hands of Panum, has failed to penetrate the mystery.

The modern form of the Nativistic Theory, as formulated by Hering[1] is, strangely enough, a mixed descendant of the theories of Johannes Müller, Lotze, Meissner, Nagel and Panum. Its assumption of specific space-sensations as constituting the

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copy of this work. His knowledge of Panum's position has been obtained at second-hand from the numerous discussions in the literature.

[1] Ewald Hering: *Beiträge zur Physiologie*, 1861-4; *Die Lehre vom binocularen Sehen*, 1868; *Raumsinn des Auges*, in Hermann's Handbuch der Physiologie, 1879, III, p. 343.

local coloring of the visual image is a characteristic of the theories of Müller and Panum; its nomenclature had already been given to the world by Meissner, and its advocacy of the dependence of the space-value (or local sign) upon distance and direction from the retinal meridians is also found in Lotze and Meissner. However, it must be recognized that Hering has worked out the Nativistic theory with greater detail than any of his predecessors; and if in its present form the theory has suffered most from hostile criticism, this is doubtless due to the fact that the modern form can be more clearly envisaged and its inherent nativistic limitations more clearly seen.

The theories of Lotze and of Hering have in common the assumption that to every retinal point belongs its own space-value; and in both theories this space-value is a function of the distance and direction of the point in question from the *fovea centralis*. But whereas Lotze assumes that the space-values (local signs) come to consciousness *indirectly*, *i. e.*, through the mediation of the sensation aroused by the movement required to transfer the image from that point to the fovea, Hering assumes that space-values come *directly* to consciousness, as sensations in their own right. To Hering, then, the stimulation of any retinal point gives rise to a two-fold sensation: a light sensation, whose attributes are essentially determined by the character of the objective stimulus, and a space-feeling, whose nature is determined by the position of the retinal point stimulated. Nagel had called attention to the familiar fact that the position of a point in external space is determined when we have determined its direction and distance from the fovea. But whereas Nagel derived our determination of these two spatial relations from sense-data,[1] Hering posits specific retinal sensations of direction and depth. The former he again subdivides into feelings of breadth and of height; so that the space-feeling which arises on the stimulation of any retinal point has a three-fold content: a feeling of breadth, of height and of depth. The fovea, as for Lotze and Meissner, is the central point or point of reference of the whole space-system, and itself possesses a space-value = 0. The space-value which accrues to an individual retinal point, in virtue of the space-feelings aroused on the stimulation of the point, are not absolute but relative only. Hering's space-feelings therefore provide merely for relative space-localization,—localization in relation to a given nuclear point of visual space. This nuclear point (*Kernpunkt*) coincides approximately with the momentary point of fixation.

This theory makes no use of eye-movements in its account of the origin of spatial vision. Indeed, Hering explicitly

[1] A. Nagel: *Das Sehen mit zwei Augen*, 1861, pp. 178 ff.

asserts that, in binocular vision at least, eye-movements are the effect, not the cause, of the perception of depth.[1]

Moreover, since the seeing of depth is, for Hering, a function of the relative position of the images upon the two retinas, it is evident that his theory is unable to explain the monocular estimation of depth. Since Hering follows Panum in making depth vision a product of the simultaneous co-operation of the two retinas, he is forced either to deny to monocular vision the possibility of estimating depth, or to eke out his theory by supplementary hypotheses in order to account for this possibility. Of the two evils he chooses the latter; but in so doing he is forced to the damaging admission that the difference between monocular and binocular depth estimation is not one of degree only, but is an essential and absolute difference. The latter is immediate, while the former is mediated by accommodation;[2] they are as distinct from each other as are the processes of sensation and of inference.

Besides the Nativistic and Empiristic theories discussed above, there has also been advanced a Genetic theory of visual space. The latter is an off-shoot from the Empiristic stem; its origin may be traced to a series of experiments performed by Wundt during the years 1858 to 1862.[3] The object of Wundt's investigation was to determine the influence of accommodation and convergence upon the perception of depth. In his experiments, a fine black silk thread was suspended vertically at a point between an observation-tube and a distant white background. Experiments were made in both binocular and monocular vision, the same method being employed throughout both series. The observer looked through the tube, and, after fixating the thread in its first position, turned his head while the thread was being moved to a new position. He again looked through the tube, fixated the distant background, then refixated the thread, and judged whether the movement of the latter had been in the direction of approach or recession. In this way were determined the limens of approach and recession for a series of distances ranging from 40 cm. to 250 cm. The monocular experiments yielded two general results: (1) The observer was unable to form any definite estimate of absolute distance, but could perceive changes of distance within certain limits; (2) the limens of recession were invariably greater than those of approach. The binocular experiments showed less indefiniteness in the estimation of absolute distan-

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[1] *Beiträge*, p. 320.

[2] *Raumsinn des Auges*, p. 546.

[3] *Zeitschrift für rationelle Medicin von Henle und Pfeufer*. These papers were collected and published under the title, *Beiträge zur Theorie der Sinneswahrnehmung*, 1862.

ces, though the estimate invariably fell short of the actual distance (ranging from 1/3 to 1/2 of the actual distance). Here, too, however, differences of distance were correctly estimated within certain limits, and these limits were considerably narrower than those in monocular vision. Indeed, the results indicated a 2.5 to 4.5 times greater sensitivity to depth in binocular vision. The difference between the limens of approach and recession vanished in the binocular series. Wundt concluded that, in the latter series, the comparison of two distances was a comparison of two convergence positions by means of muscular sensations, and that the perception of distance was essentially conditioned by this sensation factor. He put a different interpretation, however, upon the monocular results. Since accommodation from a farther to a nearer point is accomplished by a muscle contraction, and may, therefore, be assumed to be attended by a muscular sensation, while accommodation from a nearer to a farther point is accomplished by a release of muscle contraction, and cannot, therefore, give rise to any muscular sensation, Wundt concluded that accommodation is capable of contributing to the perception of change of distance only in the direction of approach. He was of the opinion that, in his monocular experiments, the perception of the recession of the thread was rendered possible solely by the change in the size of the visual angle subtended by the receding thread.

The net results, then, of Wundt's investigation are his conclusions that in binocular vision the perception of approach and recession is the resultant of sensations of convergence, while in monocular vision the perception of approach alone is the resultant of sensations of accommodation.

Wundt is essentially an orthodox Empirist in his interpretation of these results. In the opinion of the earlier advocates of Empirism, our knowledge of spatial relation is the product of a distinctly conscious process. The 'visual sign' is present in consciousness as such; the judgment of the distance signified in a conscious inference. The substitution of an unconscious inference made its appearance in the later forms of the theory. This was especially characteristic of the view of Helmholtz and was characteristic also of Wundt's earlier theory. "With the accommodation is associated a feeling in the eye from which an inference is drawn as to the approach of the observed object."[1]

The Scottish school assumed a process of association to explain the origin of visual ideas of space. Thus, in the system of Bain, the association of retinal sensations with sensations of

[1] Wundt: *Beiträge*, p. 109.

different intensity arising from ocular movements, gives rise to ideas of linear and two-dimensional space. The perception of depth is traced to an association of retinal sensations with sensations of convergence and accommodation.

In his later writings on psychological space Wundt modifies his earlier view. His theory of Complex Local Signs assumes a characteristic psychical process to account for the perception of space.

Meanwhile the experimental investigation was continued with renewed vigor. Helmholtz[1] describes an illusion which shows the influence of accommodation upon the estimation of distance. "At the end of a tube, blackened on the inside, I set up a screen pierced by two vertical slits which were covered, the one with a red and the other with a blue glass. A noticeably greater effort of accommodation was required to see the red line distinctly than was the case with the blue. Finally after numerous trials I got the impression that the red line stood out nearer than the blue."

In 1894 Hillebrand contributed a paper to the discussion.[2] Hillebrand objected that binocular experiments are inadequate to a solution of the problem since the use of two eyes introduces secondary criteria, notably crossed and uncrossed double images, and thus prevents an isolation of the influence of the factors of accommodation and convergence. His experiments dealt with monocular vision alone. They were concerned chiefly with an investigation of the relation between accommodation and depth localization; but, since accommodation and convergence are intimately associated physiologically, the influence of convergence was not excluded. He also objected to the employment of a thread as fixation-object, since the change in its apparent diameter with change of distance and inequalities in the thread itself may furnish a clue to distance estimation, and thus defeat the end of the investigation. In Hillebrand's apparatus the clean-cut edge of a black cardboard screen was brought into the median plane of the field of vision,—the screen thus hiding half of the distant white background. The mathematical line which marked the boundary between the black and the white halves of the field of vision served as fixation-object. A mechanical device enabled him to expose this fixation-object at any distance (up to one meter) from the observer, to move it gradually towards or from the observer, and to remove it abruptly from the visual field and to replace it immediately by another similar screen-edge at a

[1] H. Helmholtz: *Phys. Optik*, 1867, 634; 1897, 779.

[2] F. Hillebrand: *Das Verhältniss von Accommodation und Convergenz zur Tiefenlokalization.* Zeitschrift für Psychologie und Physiologie der Sinnesorgane, VII, 1894, p. 98.

different distance.[1] Hillebrand's experiments assumed two general forms. In the first series the screen was gradually moved towards or from the observer, the sliding movement being begun before the screen was exposed. The movement itself was constant and its rapidity was so gauged that the observer could conveniently follow with his accommodation; *i. e.*, the movement was so slow that change of accommodation could readily keep pace with it; dispersion circles were, therefore, never present in any considerable degree. In the second series two screens were employed; after the first had been fixated for a time, it was *abruptly* removed laterally from the field of vision, and the other was immediately brought in at a different distance, the observer being required to state whether in the second case the distance was greater or less than in the first.

When the change of distance was *gradual*, the observers were unable to state the direction of the movement of the fixation-object, although it seems clear that changes of accommodation must have occurred during the movement. From the negative character of the results of this series, Hillebrand concluded that muscular sensations of accommodation either are non-existent, or at least are inoperative in the perception of depth. For this conclusion he finds additional confirmation in the results of his experiments with an Aubert diaphragm. This instrument he fastened to the screen of his apparatus, and in a series of experiments, he found that, if the aperture in the diaphragm was continuously increased or decreased while its distance from the observer remained constant, a distinct impression of recession or approach arose, although the accommodation had meanwhile remained unchanged. When the diaphragm gradually approached, its aperture meanwhile being *rapidly* decreased, there arose an impression of recession, notwithstanding the greater tension of accommodation.

In the series where the distance of the fixation-object was *abruptly* changed, he found distance-limens, before which and beyond which approach and recession were perceived almost without error. These limens are invariably much larger than those of Wundt, ranging from one to two diopter-differences for approach, and from one to four diopter-differences for recession. The excess of recession limens over those of approach which Wundt's monocular experiments showed, was found with only three of Hillebrand's five observers.

How are these correct estimates of relative distance to be

[1] For cut and detailed description of Hillebrand's apparatus, see his paper, *loc. cit.*, p. 108. The apparatus employed in our own experiments was modelled after Hillebrand's. It is figured and described below, p. 170 ff.

explained? Hillebrand admits that the assumption of accommodation-sensations would furnish a satisfactory explanation, were it not for the fact that his observers were unable to estimate gradual changes of distance. In view of this latter fact he considers the existence of accommodation-sensations as exceedingly problematic and their influence as inoperative. He therefore rejects Wundt's theory and casts about for a more satisfactory explanation. From the introspections of his observers he forms a conjecture as to the manner in which any required adjustment of accommodation is made. This conjecture he confirms by experiment and advances as an explanation of his results.

This explanation is as follows: When a point, which is not equidistant with the point of fixation, appears in the field of vision, it images itself upon the retina in dispersion circles. The observer forthwith sets about to effect that adjustment of accommodation which will give rise to clear vision. But he does not know as yet whether greater or less tension of accommodation is the appropriate movement. Either of the two possible movements is chosen at random and deliberately innervated, the effect upon the definition of the retinal image being noted meanwhile. If an improvement in definition follows, the movement is continued until perfect definition results. If, however, the dispersion images are increased by the initial movement, it is abandoned and the opposite movement is chosen and continued until clear vision is attained. Hillebrand performed a series of experiments whose results showed that adjustment of accommodation for a second point requires less time when the observer knows whether it is nearer or farther than the fixation point, than is required when its direction from the fixation point is unknown. This confirms his suspicions as to the manner in which adjustment of accommodation is made, the excess of time required in the case of unknown direction representing the time lost in experimental tests which result in the appropriate movement being finally hit upon. Accordingly, Hillebrand concludes that the conscious impulse of will (*bewusster Willenimpuls*) which innervates accurate adjustment of accommodation from a first to a second fixation point, is the determining factor in the relative depth localization of the second point.

The net results, then, of Hillebrand's investigations are as follows: Muscular sensations of convergence and accommodation do not contribute to depth localization. The adjustment of accommodation from one point to another is accomplished by an impulse of will. And it is the consciousness of this impulse of will which determines the relative depth localization of the second point.

In 1895 Dixon published a paper describing a series of ex-

periments which he had made with a modified form of Hillebrand's apparatus.[1] In the latter's experiments, the normal and the comparative fixation-objects were imaged upon opposite sides of the retina. In order to remove this objection, and also to shorten the time between their exposures, Dixon devised a modification of the original apparatus which exposed both screens at the same side of the field of vision. Dixon finds no essential difference in principle between Hillebrand's gradual and abrupt experiments. Since the latter form seems better adapted to give definite results, he employed the abrupt change of distance almost exclusively in his investigation. His experimental results agree in the main with those of Hillebrand, but his conclusion is widely different. Each of his observers was able to estimate changes of distance correctly but the capacity varied greatly in different individuals. Wundt's observation, that changes from far to near were more accurately perceived than changes from near to far, was not confirmed in every case. Introspection showed that in all observers "the actual criterion of depth was a difference in the rapidity or ease with which the accommodation adjusted itself (or was adjusted by the observer) and not in any conscious direction of the accommodation by the observer." He is not convinced of the soundness of Hillebrand's argument against the muscular sensation theory of depth perception, though he himself makes no use of muscular sensations in accounting for the depth localization of his own observers.

In 1896 Arrer published new experimental data together with an historical and critical discussion of the whole problem.[2] Arrer's apparatus and method differed little from those of Wundt. Indeed, such modifications as were introduced were made at the suggestion of Wundt himself. Threads were employed as fixation-objects; experiments were made in both binocular and monocular vision. Arrer also repeated Hillebrand's experiments with a duplicate of the latter's apparatus and obtained similar results. Two objectionable features of Hillebrand's apparatus were pointed out by Arrer: the juxtaposition of the white and the black portions of the field of vision gives rise to such a degree of contrast and irradiation as renders accurate accommodation uncertain if not impossible. Moreover, the fixation of a mathematical line brings with it no definite idea of its absolute depth, and Arrer is convinced from his investigation that without a definite presentation of abso-

[1] E. T. Dixon, On the Relation of Accommodation and Convergence to our Sense of Depth, *Mind*, N. S., IV, 1895, p. 195.

[2] M. Arrer: *Ueber die Bedeutung der Convergenz- und Accommodationsbewegungen für die Tiefenwahrnehmung*, *Phil. Stud.*, XIII, 1896-7, p. 116 ff.; p. 222 ff.

lute distance, perception of relative distance is impossible. Accordingly, Hillebrand's apparatus is rejected as being inadequate to a positive solution of the problem. Arrer defends his binocular experiments against Hillebrand's attack, maintaining that, as a matter of fact, double images were invariably lacking from his experiments, nor did their intentional production furnish anything but a disturbing factor. He also defends the use of threads as fixation-objects. A mathematical determination of the amount of variation of visual angle with approach and recession of the thread in his experiments convinces him that this variation falls below the minimal values which have been determined for the just observable difference of visual angle.

Arrer's monocular experiments gave a somewhat greater liminal value than his binocular, though monocular perception of difference of depth was fairly definite. Wundt's difference of limen for approach and recession was not a characteristic of all observers.

Arrer concluded that Wundt's explanation of the perception of monocular recession is not valid. He ascribes to convergence sensations the leading rôle in depth perception in his monocular as well as in his binocular experiments. The closed eye converges, approximately at least, upon the fixation point, probably being guided in its movement by the accommodation of the seeing eye. This indirect and problematic influence seems to be the sole factor which Arrer conceives to be contributed to depth perception by accommodation.

The net result of Arrer's investigation is his conclusion that the sense-factors of depth-localization, absolute and relative alike, are the sensations of convergence and accommodation. The estimation of depth occurred neither through an immediate perception of the degree of convergence strain, nor through convergence-sensations being experientially associated with the object to be localized. Sensations of convergence and accommodation are, however, those elements in our ideas of space by which reference to depth is conditioned for consciousness.

In 1897, Hillebrand contributed a second paper to the discussion.[1] In view of the fact that the experimental results which he had previously published were subsequently confirmed by Arrer and by Dixon, he finds it unnecessary to bring forward new experimental data. He now reviews the history of the problem and discusses its essential features and immediate bearings upon space theories in general. He restates his objections to the method and apparatus of Wundt and Arrer, criticises

[1] F. Hillebrand: *In Sachen der optischen Tiefenlocalization*, *Zeits. f. Psych.*, XV, 1897, p. 70.

the conclusions of Wundt, Arrer and Dixon, discusses and defends Hering's theory of space, meets the objections raised by his critics and intrenches himself in the position assumed in his previous paper.

In his most recent contribution to the psychology of visual space, Wundt devotes a section of his paper to a discussion of this problem.[1] He meets Hillebrand's objections to his earlier experiments—the influence of double images and change of visual angle—and discusses the possibility of explaining his experiments from convergence alone. He, in turn, objects that Hillebrand's fixation-object was not really a mathematical line, but an indefinite band, shading off from white into black. Accurate accommodation upon this band is impossible, hence the negative character of the results obtained by Hillebrand. It is true that, in the abrupt series, a relative localization of this fixation-object was possible, but there is evidence in the results of Dixon and Arrer that this possibility was due to the presence of secondary criteria of depth. Since these criteria were doubtless introduced because of the absence of normal conditions of accommodation, the inadequacy of Hillebrand's experimental conditions for a positive solution of the problem is evident.

Wundt further maintains that Hillebrand's theory of voluntary innervation does not furnish a satisfactory explanation of depth-localization. The assumption that eye-movements are a pure function of the will is in direct opposition to familiar facts of experience—to the difficulty of isolating a given position of accommodation from its concomitant position of convergence, and to the well known tendency of the eye to turn towards the electric spark in dark-room experiments.

Wundt's and Arrer's results indicate that a much more definite idea of distance is associated with convergence than with accommodation. But just what is the relative contribution of each to the resultant perception of depth must remain for the present an open question.

According to Wundt, the sensations arising from eye-movements are not merely muscular, but are also tendinous and pseudoarticular,—the latter arising from the rotation of the eye-ball in its socket. In small excursions these sensations are not present to consciousness, as such, simply because they fuse immediately with other sensations to form perceptions of space. An analogy is found in the case of arm-movements. When the excursion of arm-movement is small, the movement is still perceived, though the joint sensations are not present as such.

[1] Wundt: *Zur Theorie der visuellen Raumwahrnehmung*, *Phil. Stud.*, XIV, 1898, p. 1, esply. pp. 11-16.

This is but an example of a law that holds for all sense-perception; namely, that sensations of moderate intensity fuse completely to form perceptions. The formation of complex spatial ideas from sensations of ocular movements is, then, but a case of psychical assimilation.

Wundt's present theory[1] is a product of many years' growth. Wundt is of opinion that the idea of space cannot be assumed to arise from light sensations in themselves. The spatial order is the resultant of a combination of sense-data which taken separately possess no spatial attributes. His theory of Complex Local Signs takes its origin from the fact that the eye is at once an organ of vision and of movement. Each of these modes of functioning furnishes a system of local signs; and by local sign Wundt means any datum for consciousness which is effective in the localization of an impression. It is a well-known fact that the same stimulus may arouse qualitatively different sensations at different parts of the retina. Accordingly, Wundt assumes that every sensation possesses its own peculiar local coloring, corresponding to the part of the retina stimulated. These qualitative differences constitute a first system of local signs. Since the movements of the eye are attended by sensations of muscular and orbital origin, they are able to furnish a second system of local signs. Moreover, these two systems are brought into intimate relation by the reflex transference of eccentric impressions to the center of the retina; consequently they may be regarded as a single system of complex local signs. The psychical process which gives rise to the perception of space is a fusion. And it is characteristic of the fusion that the component sense-data are so closely merged in a single product that they are not discernible as sense-data. In the opinion of Wundt, then, eye-movements are an essential factor in the perception of space. Changes of convergence are accompanied by sensations which constitute an important element in the binocular perception of depth; accommodation furnishes sensations which, though assigned a minor rôle, come into play in the monocular perception of depth.

An investigation into the visual perception of space has recently been made by Bourdon.[2] In addition to accommodation and convergence Bourdon mentions, as monocular depth factors, the nodal and pupillary parallaxes and the monocular parallax. The latter refers to changes in the position of the

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[1] Wundt: *Logik*, 1880, pp. 437 ff., *Outlines of Psychology*, 2nd. English Edition, 1902, pp. 113 ff., *Grundzüge der physiologischen Psychologie*, 5th Edition, 1903, II, pp. 501 ff.

[2] B. Bourdon: *La perception visuelle de la profondeur*, *Revue philosophique*, 1898, XLVI, pp. 124 ff. *La perception visuelle de l'espace*. Paris, 1902.

eye as a result of movements of the head; by the pupillary and nodal parallaxes are designated changes in the position of the pupil and nodal points relatively to the position of the visual object. Bourdon attaches but slight importance to accommodation as a factor in the monocular perception of depth. Binocular convergence occurs even in monocular vision and furnishes a clue to distance. The pupillary and nodal parallaxes give only a very imperfect knowledge of depth. Of all the possible factors, the monocular parallax is the most important in the monocular perception of distance. Bourdon publishes the results of experiments which he performed with a view to determining the influence of convergence and accommodation in the monocular estimation of distance. In the comparison of two distances—2 m. and 6.5 m.—successively marked off by electric sparks, he found that changes in the direction of approach are much more accurately perceived than changes in the opposite direction. When the two distances were given simultaneously, the results were negative. The absolute estimation of distance is extremely uncertain in monocular vision.

In his first series of binocular experiments two luminous objects appeared successively in the observer's median plane. The standard distance was 1 m. and the comparative distances 1.08 m., 1.12 m. . . . up to 1.32 m. His results show that for one subject the differential limen was less than .08 while for the other it lay between .16 and .20. In his second series of binocular experiments, he employed distances ranging from 10 m. to 25m.; lanterns at the ends of a dark L-shaped passage-way served as fixation-objects. The observer stood at the intersection of the two arms of the passage-way; after fixating the first lantern he turned on his heel through 90° and fixated the second. The results show a preponderance of right judgments only when the ratio of the two distances was 1:2 or more. An obvious source of error is to be found in the crudeness of the method employed in the second series of binocular experiments. Since the observer was directly opposite a corner of the wall and but a few feet removed from it, there is no guarantee that the first position of convergence and accommodation was not lost and forgotten before the second was assumed. Moreover the most zealous advocates of the influence of convergence and accommodation have never maintained that this influence is operative save in the perception of near distances.

An historical survey of the literature of depth-perception reveals the existence and progressive development of two distinct types of theory.[1] The one dates from Descartes and

[1] Wundt proposes a different classification. *Logik*, pp. 452 ff.

Berkeley and culminates in Helmholtz; the other may be traced from Johannes Müller to Hering. The genetic theory of Wundt occupies, to some degree, a mediating position between the two extremes. Of these three later views, only those of Hering and of Wundt are discutable at the present day. Original as these men are, they represent theories which contain no essential element—save only Wundt's conception of the nature of the space-fusion—which is not considerably older than its modern advocates.

The problem of the visual perception of depth has been before the world for nearly four centuries; yet, though it has engaged the attention of the best scientific minds of that period, in only four instances—Wundt, Hillebrand, Arrer and Dixon—has it been submitted to even an approximately adequate experimental test. If our results are, as we believe they are, decisive, they furnish yet another instance of the celerity and certainty with which the experimental method can deal with disputes of long standing.

The present status of the problem may be summarized as follows:

The only point upon which agreement has been reached is the bare general fact that the motor adjustment of the visual mechanism contributes to depth-localization. As to what is the character of this contribution, and the manner in which it is made, there is, as we have seen, a wide diversity of opinion.

In the opinion of Hillebrand, we must ascribe to accommodation the rôle of furnishing dispersion images, and of occasioning thereby a voluntary impulse to innervate a readjustment of accommodation, appropriate to secure perfect definition. This conscious adjustment of accommodation (or, more properly, the innervation which ushers it in) is the determining factor in the monocular depth-localization of the fixation-point, under the conditions of his experiments.

According to Dixon, the difference in the degree of rapidity or ease with which the readjustment of accommodation came about was the actual criterion of depth in his experiments. According to Wundt and Arrer, changes of convergence and concomitant changes of accommodation furnish muscular sensations which, in turn, constitute the sense-factors of our perceptions of tridimensional space.

II. Experimental.

i. *Apparatus.* The possibility of solving this problem experimentally reduces, in the last analysis, to the possibility of devising a means of isolating the influence of the convergence and accommodation factor, and of determining how, and in

what degree, this factor, unaided by any other depth criterion, is capable of contributing to depth-localization. Hence a fundamental requisite of the apparatus to be employed is that it shall render inoperative all depth criteria save only that of accommodation and convergence. It is, of course, essential that depth-localization by means of accommodation and convergence shall be possible under the conditions of the experiment.

The form of apparatus devised by Hillebrand seems to meet the requirements of the present investigation. The exclusion of binocular vision is the simplest means of eliminating the criterion furnished by disparity of retinal images. The co-operation of the factor arising from change of size of visual angle is most satisfactorily ruled out by choosing for fixation-object an object whose size does not change with change of distance. It is true that Wundt and Arrer have raised serious objections against this apparatus. They found that the influence of irradiation and contrast renders Hillebrand's fixation-object so indefinite and obscure that accurate accommodation upon it was impossible. This may, conceivably, be the case with strong degrees of illumination-intensity of the background. But with moderate intensity of illumination, it is certainly not the case.[1] No one of our five observers, no one of the numerous visitors who interested themselves in the apparatus, ever failed to see the screen-edge as a clear-cut, well-defined line, or experienced the slightest difficulty in accommodating accurately upon it, so long as the screen stood beyond the near-point of accommodation. That this objection is invalid, that accommodation, under Hillebrand's experimental conditions, is possible and practicable, is abundantly proved by the accurate distance-estimates of which our observers were capable.

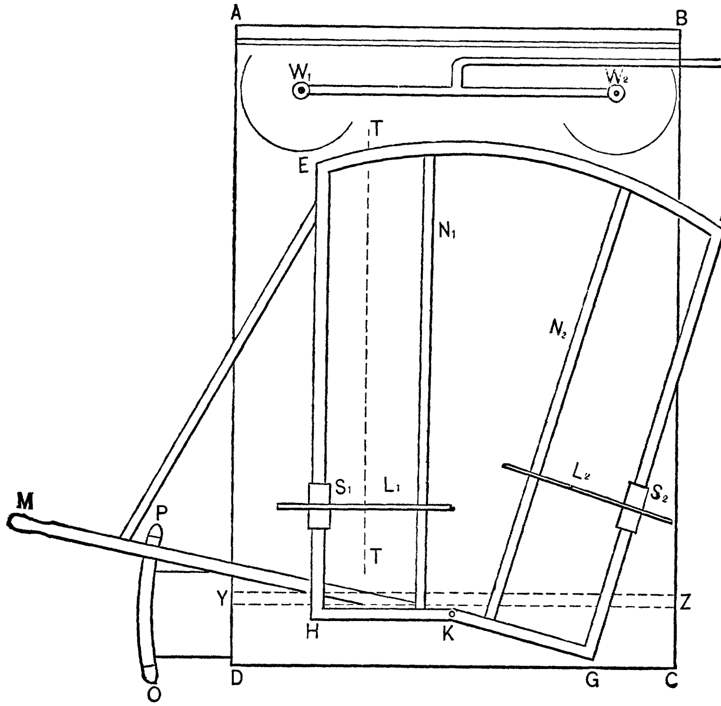
To Hillebrand, then, we are indebted for the apparatus.[2] We have modified it only in non-essential details.

In Figure 1, ABCD is a table 130 cm. wide and 140 cm. long. At AB is erected a vertical sheet of ground opal glass (80 cm. by 100 cm.), which serves as the background. EFGH is a stout wooden frame, pivoted to the table at K, and suspended at E and F from a 25 foot ceiling. On EH and FG are fitted slides, S_1 and S_2, each carrying a vertical screen, L_1 and L_2. A lever, M, is attached to the swinging wooden frame at H, and secured by a brace from E. A wooden arc, OP, is fastened to the side of the table, and provided with padded blocks at O

[1] The intensity of the light reflected to the diaphragm of our observation-tube was equal to the direct light of a standard candle at a distance of 56 cm.

[2] For Hillebrand's figure and description, see his first article, *Zeits.*, VII, 108 ff.

and P. These blocks are so adjusted that when the lever is pressed against O, the edge of the screen L_2 just comes to the longitudinal center of the table, and when the lever is brought up against P, the edge of L_1 is swung to the center of the table.



On the under side of the lever is fitted a padded block, provided with a spring so arranged as to press against the wooden arc, and thus to lock the swinging frame when it has reached the end of its excursion. The suspension of the frame from the ceiling, and the heavy padding of the stop-blocks render the operation of the apparatus noiseless. A shelf-like attachment, fastened to the screen YZ, a few inches above, and parallel to, the table, incloses the part of the apparatus which projects under the screen. The background is illuminated by two Welsbach gas burners, W_1 and W_2, shaded by vertical semi-cylindrical shades of blackened tin. A vertical screen (80 cm. by 100 cm.) is built across the table at YZ. At a convenient height, a brass observation-tube is let into this screen. This tube, which is lined with black velvet, is 40 mm. in diameter and 50 mm. long. Its end farthest from the observer is

provided with a diaphragm containing an aperture 10 mm. wide and 15 mm. high. The tube projects from the screen towards the observer, and is so adjusted that, when the observer is in position, the center of rotation of his eye is vertically over the pivot, K. The inner side of the screen YZ is covered with black velvet to prevent reflection of light to the front of the observation screens, L_1 and L_2. It is also provided with an automatic shutter which closes the diaphragm of the observation-tube. On the outer side of the screen YZ an adjustable chin-rest is fitted. The wooden bars N_1 and N_2 are inserted for the purpose of supporting the bases of the screens L_1 and L_2, thereby ensuring a vertical position of the screen edges.

The most carefully constructed parts of the apparatus are the screens, L_1 and L_2. These screens are 32 cm. wide, 75 cm. high and 8 mm. thick; they are constructed of veneered wood to prevent warping. Along the inner edge of each screen is fitted an L-shaped strip of brass. After the brass had been fastened to the screen, its free edge was carefully worked down by a surface plate to a perfect straight-edge. Then the surface of the screen where the brass and the wood are joined was ground down to an uniform surface, filled with molten wax, painted, sandpapered and repainted until it presented an uniform dead-black surface. The joint was barely perceptible in daylight; it certainly could not be detected in the dark-room where the experiments were performed.

ii. *Method.* The object of these experiments was to determine the limens of approach and recession of the fixation-object for various distances, ranging from 286 mm. (3.5 diopters) to 666 mm. (1.5 diopters). The experiments assumed two general forms: (1) with *abrupt* change of distance, and (2) with *gradual* change of distance.

(*1*) *With abrupt change of distance.* The method employed in this series of experiments was a serial method, without knowledge. The observer seated himself comfortably before the observation-tube; after a pause of from seven to ten minutes for adaptation, he received a signal and brought his eye to the observation-tube. The shutter was opened, and he was asked to assume such a position that half of his field of vision was black and half was white. Then he was required to fixate the screen-edge carefully. When he had secured perfect accommodation upon the fixation-object, he gave a signal; the experimenter grasped the lever, and swung the frame until the lever touched the block at the other end of the wooden arc, thus bringing the second screen-edge to the exact center of the observer's field of vision, but at a different distance.[1] The observer fixated it,

[1] Dixon believes that the interval of time elapsing between the removal of the first screen and the exposure of the second was too

and judged whether it was nearer or farther than the first. Then the shutter was closed, introspections were recorded, and after a brief pause the experiment was continued. The observer was cautioned throughout to adjust his head so that the fixation-object was imaged upon the central vertical meridian of his retina, to move neither his head nor his eye during the observation and to announce the first symptom of fatigue.

In this manner the limens of approach and recession were determined for five distances,—286 mm. (3.5 D), 333 mm. (3.0 D), 400 mm. (2.5 D), 500 mm. (2.0 D) and 666 mm. (1.5 D). Ten liminal values of approach and ten of recession were determined for each of the five distances. The average limens, with the mean variations will be found in the tabulated results.

(2) *With gradual change of distance.* A slight modification of the apparatus was found to be necessary for these experiments. The method employed was as follows: the shutter was opened and the observer fixated the screen-edge. When he had acquired a perfect accommodation, he signalled, whereupon the experimenter pushed the screen towards or from him,—the movement being constant and of such rapidity that accommodation could follow it without difficulty. The movement was made by hand, but a considerable degree of constancy and uniformity was soon acquired. The rapidity used in these experiments was approximately 10 cm. in 7 seconds.

It was found early in this series that the sound of the moving slide furnished the observer with a clue to the direction of the movement. Even when the shutter was closed, some of the observers were able, from sound alone, to estimate the direction of the movement with surprising accuracy. Since the presence of this factor would render impossible the isolation of the criteria with which we are concerned, the following plan was devised.

The wooden frame EFGH (Figure 1) was removed from the apparatus. One of the screens, S_1, was taken from its slide and mounted upon a carriage with grooved wheels. A smooth, hardwood track was constructed upon the table (along the dotted line, T) and the carriage set upon it. Our first plan included a pair of parallel tracks upon the table, but it was found impossible to make them sufficiently smooth for our purpose. An almost infinitesimal tremor of the moving car

long and thus tended to render judgments inaccurate and uncertain. We confess that we cannot see any ground for this objection. However, to obtain a measurement of the time required, we arranged an electric contact mechanism, and recorded the time-intervals upon a kymograph. The average duration of the interval (4 series,—each of ten individual tests,—made at different stages during the progress of the experiment) was $1.02 \pm .06$ seconds.

was magnified into a noticeable lateral swing of the screen-edge. The difficulty was overcome by building a second track at the top of the screen. Great care was taken in planning the tracks; the result was a movement of the screen without perceptible tremor and without a trace of noise.

iii. *Results.* The experiments whose results are given below covered a period of time extending from November, 1901, until June, 1902. Each observer gave two one-hour sittings a week throughout that period. The observers were: Dr. I. M. Bentley (*B*), and four graduate students in psychology, Miss B. M. Downes (*D*), Messrs. R. H. Gault, (*G*), M. S. Macdonald (*M*), and H. C. Stevens (*S*).

The apparatus stood in a corner of the dark-room, where it was hidden from view by a curtain. None of the observers —excepting *B*—had any definite knowledge, before the experiments began, of the size or form of the apparatus. Not until the observer had gone into his dark corner and seated himself before the observation-tube was the curtain removed. It was always replaced again before he left his seat at the close of the sitting. So that no observer—with the single exception of *B*—had any extraneous aid in forming his judgments of the distances with which the experiments were concerned.

Observers *G*, *M* and *S* are emmetropic; *D* is hypermetropic (+ 1.18 D.). The distance of the near-point of accommodation of the eyes employed in the monocular experiments were: *B*, 143 mm., *D*, 186 mm., *G*, 132 mm., *M*, 118 mm., and *S*, 123 mm.; no spectacles were worn in any of the experiments. *B's* eyes are defective in that they possess what may perhaps best be described as an unusually great inertia of accommodation. He finds that after accommodating continuously on a near object, he is unable for some time to get a clear image of distant objects. Thus, after reading for an hour or two, he is able only after the lapse of fifteen or twenty minutes to recognize a friend on the opposite side of the street. Whether the difficulty is due to a muscular or lenticular (*i. e.*, decreased plasticity) defect we cannot say. Unfortunately no oculist within reach has been able to diagnose the case, or to make a quantitative determination of the defect. We hope later on to be able to give a more exact characterization of the case.

The experiments fall into five groups: (A) Monocular experiments, in which the change of distance was made abruptly; (B) Binocular experiments in which the distance changed abruptly; (C) Monocular experiments with gradual change of distance; (D) Monocular and (E) Binocular estimations of absolute distance.

Our chief concern will be with the results of group (A). The binocular experiments were made solely for purposes of comparison.

(*A*.) Monocular Abrupt Series.

The object of these experiments was to determine the limens of approach and recession (as defined below) for five standard distances—286 mm. (3.5 D.), 333 mm. (3 D.), 400 mm. (2.5 D.), 500 mm. (2 D.), and 667 mm. (1.5 D.). We employed a serial method, without knowledge, working from equality in both directions. At the beginning of each series, the two screens, L_1 and L_2, were set at any one of the standard distances. Then the shutter at the end of the observation-tube was opened; the observer fixated the edge of L_1 until perfect definition resulted, gave the signal for the movement of the frame EFGH which should swing in the second screen L_2, and then fixated the edge of the latter. He gave his judgment as to the relative distance of L_1 and L_2, and his introspections. For the next exposure, L_2 was set at a different distance from the observer, nearer or farther, and the two screens were successively exposed as before. The series reached its natural conclusion when the observer was sure of the direction in which the second screen had been moved along the slide N_2. The change of distance in each successive setting of the second screen varied from five mm. to ten mm., according to the absolute distance of the standard screen. It remained constant throughout a series.

The nature and conditions of the experiment demand that each series shall proceed from equality to inequality, and never in the opposite direction. An illustration will make this evident. If in the initial exposure of any series the second distance were considerably greater or considerably less than the first, the second screen-edge would appear in dispersion images. Dispersion images would then furnish a criterion of inequality of distance; and so often as they recurred, the observer would be able to say without hesitation that the two distances were unequal. If, now,—as the procedure assumes,—he knew the relative positions of the screens in the initial exposure of the series, and knew also that the series were continuous in one direction, the criterion furnished by dispersion-images would warrant a judgment as to relative distance until equality were almost reached, *i. e.*, until the dispersion-images vanished from the series. Hence in an experimental series proceeding from inequality, judgments of relative distance would be possible without recourse to changes of accommodation and convergence.

We have, accordingly, in our experiments, proceeded only from equality. It is impossible that dispersion images could have been a contributing factor in the results tabulated below. For while dispersion images constitute a criterion of inequality of distance, they are powerless, at least under the experimental

conditions of the present investigation, to furnish evidence of the direction of inequality. They arise when the second point of fixation is nearer *or* farther than the first; they are consequently incapable of prompting a judgment that the second is definitely nearer, or is definitely farther than the first.

Each series was continued until the observer had reached a considerable degree of confidence in his judgment of nearer or farther. For the sake of convenience, symbols were employed to denote five increasing degrees of confidence. Confidence 1 denoted the minimal degree; confidence 5 denoted absolute certainty. Three approximately equal stages intermediate between these extremes were differentiated, and designated by the symbols 2, 3 and 4.

About ten determinations of each limen were made. In order that time might be saved, the series was seldom continued after confidence 3 had been reached.

(*B.*) Binocular Abrupt Series.

For this series a binocular observation-tube was fitted to the apparatus in place of the monocular tube. The observer now used both eyes in fixating the screen edge. Otherwise, the apparatus and conduct of the experiment remained unchanged.

(*C.*) Monocular Gradual Series.

A modified form of apparatus was employed in these experiments. The frame EFGH was removed; and a smooth hardwood track was made fast to the top of the table at the place indicated by the dotted line T in the diagram. Upon this track ran a carriage provided with grooved wheels. One of the screens used in the previous experiments was fastened to the carriage. About 75 cm. above the surface of the table was fitted a second wooden track parallel with the first; the screen carried on its upper edge a wheel which ran on this upper track. This device made it possible to move the screen to and fro without noise and without tremor. A metal pointer, fixed to the carriage, just cleared a millimeter scale, and indicated the distance of the screen from the observer's eye. The method of conducting the experiment was as follows. The shutter was opened, and the observer was asked to fixate the edge of the screen. When he had obtained a perfect image of the edge, he gave a signal; the screen was now pushed with a constant and uniform motion along the track. The rate of motion employed for all points of the scale was seven centimeters in ten seconds. The observer gave a signal when he first detected movement, and a second signal when he was able to detect the direction of movement.

TABLE I.

Results of Monocular Abrupt Experiments. a. Confidence 1. Showing the points at which Approach and Recession of the Second Screen were first noticed.

		286 mm.		333 mm.		400 mm.		500 mm.		667 mm.	
		Approach.	Recession.	Approach.	Recession.	Approach.	Recession.	Approach.	Recession.	Approach.	Recession.
Settings of Second Screen.	*G.*	270±2	320±13	318±1.6	384±9	375±4	458±7	474±5	563±8	618±17	750±19
	M.	260±3	318±8	305±6	373±6	357±5	458±15	450±7	566±14	593±13	760±21
	S.	258±6	325±9	305±5	376±14	360±8	456±15	446±10	565±10	596±15	747±24
	D.	255±5	334±11	288±6	403±16	352±6	506±26	444±13	604±21	578±16	798±34
Limens[1] in % of Standard Distance.	*G.*	5.6%	12%	4.5%	15.3%	6.3%	14.5%	5.2%	12.6%	7.4%	12.5%
	M.	9.1	11.3	8.4	13	10.6	14.5	10	13.2	11.1	14
	S.	9.7	13.7	8.4	12.8	10	14	10.8	13	10.7	12
	D.	10.9	16.8	13.5	21	12	26.5	11.2	21	13.4	19.7

[1] By 'limens,' as explained above, we here mean the difference in distance between the standard and variable screens at which the observer first passed judgment of 'nearer' or 'farther' with a given degree of confidence.

TABLE II.

Results of the Monocular Abrupt Series. b. Confidence 3. Showing the point at which the Approach or Recession of the Second Screen was observed with a fair degree of confidence.

	286 mm.		333 mm.		400 mm.		500 mm.		667 mm.	
	Approach.	Recession.	Approach.	Recession.	Approach.	Recession.	Approach.	Recession.	Approach.	Recession.
G.	252±7	365±12	302.6±8.3	430±32	355±16	512±26	446±17	625±31	602±12.7	847±21
M.	237±7.6	342±6	288±8	399±11	330±6	492±18.4	403±9	607.5±22	550±25	840±45
S.	247±6.6	340±10	287±4.3	402±7.4	340±8	487±11	424±8	610±32	569±18	787±49
D.	230±6.6	376±8.8	278±10	442±35	332±8.3	554±12	432±25	688±42	532±41	880±35
G.	11.9%	27.7%	9.1%	29.1%	11.3%	28%	10.8%	25%	9.8%	27%
M.	17.2	19.6	13.5	19.8	17.5	23	19.4	21.5	17.6	26
S.	13.7	18.9	13.8	20.7	15	21.8	15.2	22	14.7	19.1
D.	19.6	31.5	16.5	32.7	17	38.5	17.4	37.6	20.3	32

Table III.

Results of the Binocular Abrupt Series. Confidence 1. Showing the points at which Approach or Recession of the Second Screen was just noticed.

	286 mm.		333 mm.		400 mm.		500 mm.		667 mm.	
	Approach.	Recession.	Approach.	Recession.	Approach.	Recession.	Approach.	Recession.	Approach.	Recession.
G.	282±1.5	291.6±1	330±0	337±.8	395±0	405.7±.9	492.5±2.5	508.3±2.2	655±2.5	676.6±2.3
M.	283±0	290±2	327±1.3	340±1.5	393±1	405±0	495±1.7	507.5±2.3	656±3	679±2.8
S.	281±1.3	291±1	327±0	339±1.8	395±1.3	407±2	490±0	507±1.8	650±1.7	673±2.7
D.	277±1.5	293±2	325±.9	342.5±2.5	389±2.4	409±1.5	487.5±3	510±0	647±4	683±3
B.	280±2.3	293±1.7	328.3±2.3	338±2	392.3±1.5	410±0	493±1.3	510±0	653±2.2	680±3.3
G.	1.4%[1]	1.96%	.9%	1.2%	1.3%	1.4%	1.5%	1.7%	1.8%	1.4%
M.	1.1	1.4	1.8	2.1	1.8	1.3	1	1.5	1.7	1.8
S.	1.8	1.8	1.8	1.8	1.3	1.8	2	1.4	1.7	1.8
D.	3.1	2.5	2.4	2.9	2.8	2.3	2.5	2	3	2.4
B.	2.1	2.5	1.5	1.5	1.9	2.5	1.4	2	2.1	1.9

[1] The comparative irregularity of these binocular limens is doubtless due to the relatively small number of binocular determinations.

We give below, in separate Tables, the average limens of movement, and of direction.

TABLE IV.

Monocular Gradual Movement. Showing the points at which movement was first noticed in Approach and in Recession.

	286 mm.		333 mm.		400 mm.		500 mm.		667 mm.	
	Approach.	Recession.	Approach.	Recession.	Approach.	Recession.	Approach.	Recession.	Approach.	Recession.
G.	241	375	287	425	344	493	417	601	578	778
M.	220	365	271	420	320	515	410	622	550	807
S.	232	388	280	479	325	570	396	664	550	850
D.	225	380	289	443	328	533	415	620	552	805
B.	240	421	278	507	325	610	405	706	555	927
G.	15.8%	31.2%	13.8%	27.6%	14%	23%	16.6%	20%	13.4%	16.7%
M.	23	27.7	18.6	26	20	29	18	24	17.6	21
S.	18.9	35.7	16	44	19	43	21	33	17.6	27.5
D.	21	33	13	31	18	33	17	24	17.3	21
B.	16	47	16.5	52	19	52	19	41	16.8	39

TABLE V.

Results of Monocular Gradual Series. Direction discerned. Confidence 1. Showing points at which direction of gradual movement was first observed in Approach and in Recession.

	286 mm.		333 mm.		400 mm.		500 mm.		667 mm.	
	Approach.	Recession.	Approach.	Recession.	Approach.	Recession.	Approach.	Recession.	Approach.	Recession.
G.	229	415	272	462	323	515	388	620	520	827
M.	212	398	247	469	285	543	366	656	496	848
S.	219	407	251	516	313	596	374	679	511	873
D.	201	513	243	539	284	684	343	770	500	892
B.	183	875	196	683	197	750	234	883	242	—
G.	20%	45%	18%	39%	19%	29%	22%	24%	22%	24%
M.	26	39	26	41	29	36	27	31	26	27
S.	23	42	25	55	22	49	25	36	23	31
D.	30	79	27	61	29	71	31	54	25	34
B.	36	206	41	105	51	88	53	77	64	—

(*D.*) MONOCULAR AND (*E.*) BINOCULAR ESTIMATION OF ABSOLUTE DISTANCE.

The form of apparatus described under (C) was employed in the experiments upon monocular and binocular estimation of absolute distance. The screen L_1 was set at any one of the distances to be estimated (286 mm. up to 667 mm., and 900 mm.); the observer fixated the edge, and estimated its distance in inches.

TABLE VI.

Estimates of Absolute Distance—Monocular.

	286 mm.	333 mm.	400 mm.	500 mm.	667 mm.	900 mm.
G.	185 ± 33	236 ± 41	342 ± 52	386 ± 33	546 ± 68	603 ± 25
M.	183 ± 28	249 ± 43	354 ± 42	412 ± 46	569 ± 43	656 ± 41
S.	188 ± 46	285 ± 66	345 ± 38	452 ± 25	610 ± 33	823 ± 39
D.	163 ± 31	189 ± 34	234 ± 28	343 ± 28	439 ± 51	585 ± 43
B.	407 ± 72	367 ± 39	325 ± 46	372 ± 76	467 ± 82	435 ± 37

Relation of Estimated to Actual Distance—Expressed in Per Cents.

G.	65%	71%	86%	77%	82%	67%
M.	64	74	89	82	85	73
S.	66	86	86	90	92	92
D.	57	56	59	69	66	65
B.	142	110	81	74	70	48

III. DISCUSSION OF RESULTS.

(*A.*) MONOCULAR ABRUPT SERIES.

Several features stand out prominently in the results of these experiments. 1. The differential limens of approach bear an approximately constant relation to the stimulus distances. 2. The limens of recession are also fairly regular throughout the series. 3. The limens of approach are uniformly less than those of recession. 4. In all cases the limens are less than one would expect from Hillebrand's investigation with the same apparatus. 5. The capacity to sense differences of distance shows a well-marked individual variation. 6. The smallness of the mean

variation indicates that all four observers estimated changes of distance with a high degree of definiteness.

TABLE VII.

*Estimates of Absolute Distance—Binocular.**

	286 mm.	333 mm.	400 mm.	500 mm.	667 mm.	900 mm.
G.	198 ± 28	279 ± 25	366 ± 41	432 ± 35	513 ± 51	653 ± 48
S.	185 ± 15	233 ± 33	300 ± 38	422 ± 32	630 ± 59	884 ± 48
D.	252 ± 23	300 ± 25	348 ± 11	429 ± 51	493 ± 36	744 ± 28
B.	254 ± 11	310 ± 18	346 ± 33	422 ± 77	539 ± 58	713 ± 84

Estimated Distance in per cent. of Actual Distance.

	286 mm.	333 mm.	400 mm.	500 mm.	667 mm.	900 mm.
G.	69%	84%	92%	86%	77%	73%
S.	65	70	75	84	95	98
D.	88	90	87	86	74	83
B.	89	93	87	84	81	79

* Through an oversight, *M's* series of binocular estimates was left incomplete. Hence his name does not appear in this Table.

None of these features is peculiar to our investigation alone. Wundt's original thread experiments[1] give at least a hint of the regular increase of limen with increase of distance; while in Arrer's results[2] the regularity of increase is but little less pronounced than in our own. Wundt's early experiments brought to light the fact that approach is more readily perceived than recession; this observation was confirmed in the main by Arrer's results, though exceptions were found also by Hillebrand and Dixon. Hillebrand's investigation points to an unusually large differential limen;[3] indeed, a difference of half a diopter seems to be the smallest limen determined for any of his observers. Yet Dixon, under identical experimental conditions, found 77% of right judgments when the screens were separated by only .05 diopter difference.[4] In Wundt's experiments the limens varied between 4% and 11% of the standard distance; Arrer, also employing a thread for fixation-

[1] *Beiträge*, p. 114.
[2] *Phil. Studien*, XIII, pp. 139-142.
[3] *Zeitschrift*, VII, pp. 126-9.
[4] *Mind*, N. S., IV, p. 210.

object, obtained limens as low as 1.6%. The maximal and minimal variations determined by Arrer[1] indicate that the mean variation of his observers was even less than that of ours. Individual variations are common to the results of Hillebrand, Dixon and Arrer.

The judgments of one of our observers—*B*—are omitted from our tabulated results. It was discovered early in the course of the experimentation that *B* differed essentially from the other observers, not only in degree of readiness and correctness of judgment, but also, to all appearances, in the nature both of the criterion and the conscious process involved. *B*, *G*, *M*, and *S* almost invariably gave their judgments an instant after the appearance of the second screen; it was found that if they hesitated, even for only a few seconds, they were lost. They seldom made an error; almost never did they give a wrong judgment with any considerable degree of confidence. In 86 determinations *G* had only 5 wrong series of judgments which reached Confidence 3; *D* in a total of 83 had 4 wrong; *M* and *S* had none wrong in totals of 93 and 88 respectively. *B's* judgments never came instantaneously; after the exposure of the second screen, there always elapsed a period of hesitation during which *B* was evidently deliberating and groping about for a clue. His judgments were usually given in such terms as: "It must be farther" (referring of course to the second screen); "It is less clear-cut; I should say nearer;" "It is more distinct; I think it is farther." These judgments were never characterized by the immediacy which seemed to be a necessary condition in the case of the other observers. Attempts were frequently made to draw a judgment from *B* soon after the second screen appeared, but always without success. If the second screen came into view with its edge blurred, the indistinctness persisted for some seconds, and frequently refused to disappear even after a tedious delay. It was found to be impossible to get the full complement of determinations from *B* although he gave more sittings than any other observer. Twenty-five single judgments in the hour was a limit beyond which he could not go. He usually suffered from fatigue in the eye, towards the close of the sitting; *D*, *G*, *M* and *S* averaged 80 or 90 judgments in the hour. While they rarely made an erroneous judgment, *B* seldom carried a set through without error. Of his 53 series, 26 were absolutely wrong, even when Confidence 3 was reached.

There can be no doubt that *B's* criterion was wholly different from that employed by the other observers. The immediacy of their judgments is in striking contrast with his delib-

[1] *L. c.*, p. 142.

eration; his inaccuracy is the more surprising in view of their precision. Since his accommodation failed to change on the appearance of the second screen, or changed so slowly and uncertainly as to be attended by no definite sensible effects, he was compelled to have recourse to another criterion. He seems to have hit upon a clue in dispersion-images, and to have inferred nearness from indistinctness. If, on the other hand, the edges seemed approximately equally clear-cut, the second screen was usually judged farther, even when the two were equi-distant. He frequently reported that the screens were unequally dark, and judged the darker screen to be nearer. It is extremely doubtful if there was any difference in the brightness of the two screens. Care had been taken to make them as nearly identical in appearance as possible; no other observer discovered any inequality of illumination, and *B's* introspections in the binocular experiments make no mention of unequal brightness.

Here are the records of a few typical series:

Obs. *B*. Feb. 22, 1902. 10 A. M. Condition normal.

Distance of Standard Screen.		Distance of Variable Screen.		Judgment.	Confidence.
667 mm.	(left screen)	667 mm.	(right screen)	Second screen darker. Seems nearer.	2
667	(right)	667	(left)	Second lighter. Must be farther.	1
667	(left)	667	(right)	Second lighter. Seems farther.	2
667	(right)	667	(left)	Equidistant.	

Obs. *B*. Jan. 24. 10 A. M. Condition normal.

500—500	Equal.		
" —up to 590	Equal.		
" —600	Second less distinct. Nearer.		2.
" —608	" " " "		2.
" —616	Second less distinct but lighter.	Farther.	1.
" —624	Second less distinct. Nearer.		2.
" —632	Second less distinct but lighter.	Farther.	1.
" —640	" " " " "	Farther.	2.
" —648	Second less distinct. Nearer.		2.
" —656	" " " and darker.	Nearer.	2.
" —664	" " " " "	"	3.

Obs. *B*. March 8. 11. A. M. Normal.

333—333	Equal.		
333—up to 375	"		
333—380	Second nearer.	Cannot say why.	1.
333—390	" "	Darker.	2.
338—400	" "	less distinct.	2.
333—410	" "	" "	2.
333—420	" "	darker.	2.
333—430	" "	less distinct.	2.
333—440	" "	" "	3.

Obs. *B*. March 15.	10 A. M.		Normal.
286—286	Equal.		
289—up to 410	Equal.		
286—415	Second farther—less effort to see it.		2.
286—up to 490	" "	" " "	2.
286—495	" nearer.	Edge is blurred.	2.
286—500	" "	" " "	2.
286—505	" "	" " " .	1.
286—510	Equal.		
286—515	"		
286—520	Second farther.	More easily focused.	2.
286—525	" "	" " "	3.

During the progress of this latter series *B* remarked that he hoped for change in the direction of nearer. He fears "farther" experiments, because he does not understand how he could judge in them.

No such series of judgments was given by any other observer. The following are typical of the records given by *D*, *G*, *M* and *S*:

Obs. *M*. Jan. 2, 1902.	10 A. M.		Normal.
400—400	Equal.		
400—442	Second nearer.	Cannot say why.	1.
400—449	" farther.	Cannot say why.	1.
400—456	" "	"flashed up farther."	1.
400—463	" "	" " "	2.
400—470	" "	" " "	2.
400—477	" "	" " "	2.
400—484	" "	" " "	3.

Obs. *G*. Feb. 20.	11 A. M.		Normal.
500—500	Equal.		
500—492	"		
500—484	Nearer.	"Simply came in nearer."	1.
500—476	"	"Came in nearer."	2.
500—468	"	Slight feeling of strain with second screen.	2.
500—460	"	Slight feeling of strain with second screen.	2.
500—452	"	Feeling of strain more pronounced.	3.

Obs. *G*. March 27.	11 A. M.		Normal.
286—286	Equal.		
286—315	Equal.		
286—320	Possibly nearer.	Cannot say why.	1.
286—325	Farther.	" " "	1.
286—330	"	" " "	1.
286—335	"	Less strain with second screen.	2.
286—340	"	" " " " "	2.
286—345	"	" " " " "	2.
286—350	"	" " " " "	2.
296—355	"	" " " " "	3.

G reported a sensation of eye-strain in nearly every series. He found the sensation to be more intensive when the second screen was nearer, less intensive when it was farther. This

sensation seemed to furnish the basis for his judgments throughout the whole investigation. Only in rare cases did *D*, *M* and *S* report a sensation of strain. They usually failed to find any basis for their estimation. "It just seems nearer (farther); that is all." *G's* judgments, however, were not a whit less immediate than those of *D*, *M* and *S*. It was only when he came to introspect, that he mentioned the sensation of strain. Care had been taken to avoid the suggestion of this sensation to any observer. Indeed, when we seemed to discredit the presence of *G's* sensation of strain, he insisted the more strongly that he could not be mistaken in it. It is worth noting that the only observer who was able to discriminate between his positions of accommodation by a distinct consciousness of strain, has much lower limens of approach than the others. (See pp. 178 ff.)

Obs. *S*. Feb. 15. 3 P. M. Normal.

500—500	Equal.	
500—up to 558	"	
500—564	Slight difference. Second perhaps farther.	1.
500—572	Second came in farther.	1.
500—580	" " " "	2.
500—588	" " " "	2.
500—596	" " " "	2.
500—605	" " " "	3.

Obs. *D*. March 13. 2 P. M. Normal.

333—333	Equal. "Both horribly near."	
333—up to 400	Equal. "Very unpleasant."	
333—405	Second seems farther.	1.
333—410	" " "	1.
333—415	Farther. Simply comes in at greater distance.	2.
333—420	" " " " " "	2.
333—425	" " " " " "	2.
333—430	" " " " " "	2.
333—435	" " " " " "	3.

These specimen records show the general character of the two types of judgments and introspection. The one type is characterized by its immediacy; the most searching scrutiny failed—save in the case of *G* alone—to find any introspective evidence of the presence in consciousness of a sensation-basis for the judgment. *G's* estimations were no less direct in character, but introspection almost invariably revealed the presence of a sensation factor which made the judgment possible. The other type of judgment is anything but immediate in character. Not only was the time interval between the exposure and the judgment invariably longer, but introspection discovered conscious processes, not muscular but retinal, by which the judgment was finally mediated. Moreover, as has already been pointed out, the types are as divergent in accuracy as they are in character. We believe that we are justified in assuming

that the judgments of persons possessed of the normal power of accommodation, belong to the former type.

An attempt was made, towards the close of the series of monocular abrupt experiments, to determine how far a 'conscious impulse of will,' as assumed by Hillebrand, could play a part in the judgments of relative distance. The observers were directed to make a voluntary change of accommodation from near to far or from far to near, when the second screen appeared, and to estimate its relative distance in the light of what transpired. The results invariably tell against Hillebrand's assumption. It was usually discovered that the observers were unable to change their accommodation at will in the sense assumed by Hillebrand. It was found, however, that they could see the second screen distinctly by simply willing to see it distinctly. But *such an act of will furnished no conscious datum of central origin which could give a clue as to the direction in which the change of accommodation had been made.* In some few cases the appropriate change of accommodation was brought about voluntarily, but this procedure proved to be a hindrance rather than a help to the accurate estimation of relative distance. In short, the unanimous verdict of all four normal observers goes to show that if the judgment is not made immediately it cannot be made at all.

Whether the cultivation of such an artificial means of estimating distances as Hillebrand describes could yield good results, even in the hands of observers trained to a voluntary control of their accommodation mechanism, is exceedingly problematical. Except that he gives it a name, Hillebrand leaves us absolutely in the dark as to the basis of the judgment. From what source does the conscious datum come which serves to determine what our judgment in a given case shall be? Whence do we get the raw material which enables us to differentiate, to judge now nearer, now farther? If, with Hillebrand, we deny that peripheral sensations are aroused in the adjustment of the ocular mechanism, we find ourselves compelled either to deny the possibility of estimating space monocularly, or to resurrect the deceased theory of innervation. To choose the former alternative means to dispute the results of Wundt, Dixon, Arrer and Hillebrand himself. To choose the latter, means to maintain that the voluntary initiation of movement is attended by a sensation of central origin, whose intensity is gauged by the amount of energy put forth into the movement. This in turn means to ignore the results of several decades of physiological and psychological research, and to take one's stand upon a theory long since discarded.

The results of the twenty-seven correct determinations made

by B are appended—not for comparison, because they are for obvious reasons incomparable with the results of the other observers, but solely in the interests of completeness.

TABLE VIII.

Results of Monocular Abrupt Experiments. a. Confidence 1. Showing averages of B's Correct Determinations.

286 mm.		333 mm.		400 mm.		500 mm.		667 mm.	
Approach.	Recession.	Approach.	Recession.	Approach.	Recession.	Approach.	Recession.	Approach.	Recession.
250±4	420±12	297±5	407±39	366±9	500±17	473±4	640±13	610±12	775±25
12.6%	47%	10.8%	22%	8.5%	25%	5.4%	35%	8.6%	16.2%
b. Confidence 3.									
235±3	560±0	285±15	457±29	323±18	520±26	450±20	720±31	525±45	865±0
17.9%	96%	14.4%	37.2%	19.3%	30%	10%	44%	21.3%	29.7%

(*B.*) Binocular Abrupt Series.

The principal features of these results are: 1. The liminal values are extremely small. 2. There is a large individual variation among the observers. 3. The recession limens are in general greater than those of approach—although in about 40% of the determinations they are approximately equal. 4. The proportion of limen to stimulus is approximately constant both in approach and in recession. 5. The most striking feature of Table III is, however, in connection with *B's* results. *B's* monocular judgments of relative distance were a failure; his binocular judgments compare favorably with those of the other observers. 6. It is to be noted, too, that *G's* monocular limens—particularly those of approach—were much smaller than those of any other observer; whereas his binocular results do not differ materially from the average determinations.

The introspections of this series show the presence here of but a single type of judgment—and that of the immediate character already described. *B's* introspections differ in no essential particular from those of the other observers. He reports that "the second screen came in at a greater distance," or that "it simply stands out in front," etc. In comparatively few instances did an observer succeed in discovering the factor on which he based his judgment; it was described as a sensation of strain in the two eyes—and it occurred chiefly with near distances. The localization of this sensation was indefinite; no observer was able to state that its origin was in the external muscles of the eyeball and not in the ciliary muscle.

As in the monocular experiments, so here it was found that the judgment must be given without delay. If hesitation arises, doubt ensues and estimation becomes impossible. An introspection of *B's* reads as follows (screens at 500 mm. and 492 mm.): "The second screen stands out nearer to me. No difference in clearness; no noticeable difference in strain," and at another time: "the second simply came in nearer. After a moment I could no longer be sure that they had been different." Apparent recession on continued fixation of a near screen was remarked by all observers.

(*C.*) Monocular Gradual Experiments.

These results show that: 1. Movement was almost invariably perceived before direction was discerned. 2. Limens both of approach and of recession are higher with gradual than with abrupt change of distance. 3. Limens of approach are uniformly lower than those of recession when the change of distance is gradual. 4. *B's* limens are in every case higher than those of the other observers; indeed *B* detected no recession be-

tween the limits of 667 mm. and 950 mm. (the extreme limit of the apparatus); but 5. *B's* errors are comparatively insignificant in the gradual experiments. In a total of 90 series he had but 9 errors, 8 of which were failures to detect recession of the screen.

The introspections in this series bring to light the same two types of judgment as were found in the monocular abrupt experiments. Here, as formerly, *D*, *M* and *S* gave immediate judgments for which no evidence could be found in consciousness. *M* failed in all cases to describe the conscious process which led to his judgment. *S* reported, over and over again: "I felt it go away (come nearer). No blur; no strain." *D* was frequently startled in the approach experiments by the suddenness with which "it seems to rush up toward me." *G* usually reported perceptible increase or decrease of strain. On the other hand, *B* seemed in all cases to infer the direction of motion from the rate of blurring of the screen-edge; if the blurring increased rapidly, he inferred approach; if slowly, recession.

It was suspected that the other observers were unconsciously employing the same criterion. But the results obtained from a modification of the experiment showed that this suspicion was groundless. Series were occasionally introduced, in which the screen was made to approach with extreme slowness, and to recede with corresponding rapidity. This change of method was followed by no change in the accuracy of the judgments of *D*, *G*, *M* and *S*, but it invariably led to an error in *B's* estimation. It is safe to conclude that all of *B's* experiments with gradual change of distance are failures, so far as the muscular sensations of accommodation are concerned.

Hillebrand's observers were unable to estimate gradual changes of distance with any degree of accuracy. They usually refused even to offer a conjecture as to the direction of the movement; and when they did make a judgment, they were as often wrong as right. It is to be noted that Hillebrand's results are really incomparable with ours on account of the difference of experimental conditions. Hillebrand's movement began before the shutter was opened, and hence may be assumed to have been well under way before the observer secured his first accommodation upon it. We repeated a few of his experiments; and while we did, in some few cases, obtain positive results, still the judgments were vague and indefinite and frequently erroneous. His method was finally abandoned, for two reasons. 1. If, when, the fixation-object first comes into view, it is at once near to the observer's eye, and moving directly towards or from him, accommodation upon it must necessarily be difficult and uncertain. Hence the negative

character of the results of experiments with such a fixation-object does not justify the conclusion that accommodation *never* contributes to the perception of distance. It can only be said that experiments of this type are from their very nature inadequate to a positive solution of the problem in hand. 2. The method would be inaccurate and indefensible even if it yielded results of a positive character. For if the screen be in motion before the observer accommodates upon it, we have no means of determining its precise position at the instant when he first obtains a clear image. Hence when the judgment of 'nearer' or 'farther' is finally given, we still have no record of the initial position to which it refers. It is obviously impossible to determine the relation of two positions of accommodation, one of which is, and must remain, unknown. Hence the results of such experiments cannot contribute to a solution —positive or negative—of the problem.

It would be interesting to learn how Hillebrand would reconcile the negative results of these experiments with his assumption of a 'conscious impulse of will,' by which changes of accommodation are accomplished, and mediated to consciousness. Changes of accommodation must have come about, if the moving screen were seen in perfect definition when it stood at different distances. If, now, these changes were the product of a '*conscious* impulse of will,' how did it happen that the observer was unconscious of change of distance?

Hillebrand's experiments with the Aubert diaphragm are also said by their author to tell against the participation of sensations of accommodation in the perception of depth. He found that when the diaphragm was slowly advanced, its aperture meanwhile being rapidly decreased, there resulted a judgment of recession, notwithstanding the greater tension of accommodation. Here, again, his demonstration is as fatal to his own theory as it is to that of Wundt.

This experiment, however, is irrelevant to the question: we are not concerned with the determination of the relative significance of the various criteria of distance. It fails to disprove that sensations of accommodation may contribute to the perception of depth. That these sensations constitute the sole—or even the most effective—factor of depth-localization has never been maintained. Decrease of visual angle was obviously the determining factor in this experiment. It is not incomprehensible that a factor which is effective under favorable circumstances may be swamped and rendered inoperative under adverse conditions. From the point of view of accommodation, the change of visual angle was a distracting element of superior power. That the stars cannot be seen at noon is no proof that they are forever invisible.

D and *E*. The Estimation of Absolute Distance.

The method of recording the estimates in our experiments was not free from objection. The estimate was expressed in terms of inches; it resulted from the comparison of the perceived stimulus distance with a distance mentally reproduced. For this reason, one mnst be cautious in drawing conclusions from our tabulated results, which make a direct comparison of the recorded estimates with their objective stimuli.

Whether or not these results may be accepted as a corroboration of the principle that distance is ordinarily under-estimated in the absence of secondary criteria, they at least establish the fact that absolute distance was estimated with some degree of definiteness by our observers.

It has been asserted by Wundt[1] and repeated by Hering[2] that under conditions such as were present in our experiments, the absolute distance of the fixation-object cannot be estimated. This statement is not in accord with our results. Even at their first sitting, our observers were able to express their judgments in absolute terms. In the initial experiments they were asked to estimate, not the relative position of the second screen, but the absolute distances of both screens. This they seldom failed to do; page after page of our earlier records of the monocular abrupt experiments is filled with such results as these:

Stimulus distances.	*Estimates. (Recorded in inches but here expressed in mm.)*
333 mm.—500 mm.	229 mm. and 305 mm.
667 " —333 "	457 " " 254 "
500 " —250 "	305 " " 127 "
667 " —667 "	381 " " 381 "
333 " —250 "	254 " " 178 "
333 " —310 "	254 " " 254 minus mm.

The possibility of absolute localization cannot be denied. Our results can teach us little, however, of the capacity to localize definitely (with small mean variation) and correctly (in agreement with reality).

IV. Interpretation and Conclusions.

The object of this investigation is to determine the influence of accommodation and convergence upon the perception of depth. Our experimental results have already pointed to a positive solution of the problem.

The investigation has shown that under experimental condi-

[1] *Beiträge*, p. 107.
[2] *Raumsinn*, pp. 546-7.

tions which exclude all known criteria of depth—save only accommodation and convergence—it is still possible to perceive changes of distance. This establishes the fact that either accommodation, or convergence, or both contribute to the perception of depth.

It has shown, too, that the absence from monocular vision of normal sensitivity to relative distance is not necessarily attended by a corresponding abnormality in binocular vision. This demonstration warrants the conclusion that the factors which determine the judgment of relative distance are essentially different in monocular and in binocular vision. This conclusion is supported by the fact that the limens of approach and recession bear an essentially different relation to the stimulus-distances in the two cases.

It has also been shown that in monocular vision—when the factors present are reduced to accommodation and convergence—the presence of normal accommodation has been attended by the capacity accurately to estimate relative distances, while the absence of normal accommodation has been paralleled by an absence of this capacity. From this we conclude that *accommodation constitutes the essential criterion of depth in our monocular experiments.*

It follows from our binocular results that the essential criterion in the binocular experiments was not furnished by accommodation.

The hypothesis that increased tension of accommodation gives rise to judgments of approach is not new in the literature. This theory was advanced by Berkeley, and has never since his time been without supporters. That the judgment of recession can be prompted by the opposite change of accommodation has never been generally maintained. Indeed Wundt explicitly asserted in his original paper[1] that this position is untenable. He held that since the change of accommodation which focuses a receding object at successive distances is accommplished by the relaxation of the ciliary muscle, it cannot give rise to sensation, and hence cannot constitute the basis of a judgment. This position is the logical consequence of the theory of innervation-feelings which Wundt then advocated.

If however it be held, as is now all but universally believed, that we become conscious of change of muscular tension, not through the medium of feelings of innervation, but through concomitant peripheral sensations, there is no ground for denying that the relaxation of muscle is attended by sensible effects.

[1] *Beiträge*, p. 110.

Muscle and tendon are richly supplied with sense-organs. It is conceded that the different terms of an ascending series of muscular contractions are discriminated. It is but reasonable, then, to suppose that the individual terms may still be differentiated, when the series recurs in descending order, from tension to relaxation,—*i. e.*, from greater to less degree of contraction. Hence, we are justified in concluding that accommodation may prompt judgments alike of farther and of nearer. This simply assumes that a degree of contraction of the ciliary muscle which is attended by muscular sensation if it follow upon a lesser degree, will be similarly attended if it follow upon a greater degree of contraction.

Histological investigation has shown that the organs of the muscular sensations are anatomically akin to the cutaneous organs of pressure. Von Frey's experiments [1] demonstrate—what, indeed, cannot well be disputed—that we are able to discriminate the successive stages not only of an ascending series of cutaneous pressure, but of a descending series as well. Moreover, von Frey is convinced that the differential limen is higher in the latter case than in the former.

If now this conception be carried over from the pressure-organs of the skin to the similar organs of muscle and tendon, one would expect to find that changes of accommodation arouse muscular sensations, whether they be accomplished by muscular 'contraction' (ascending series) or by muscular 'relaxation' (descending series of contractions). These two states of muscle are not different in kind; the latter is itself formulable in terms of contraction.

Since von Frey found that the differential limen of increase of serial pressure on the skin is lower than that of decrease, one would again expect to find that the same relation obtains between the differential limens of muscular 'contraction' and muscular 'relaxation.' In fact, the results of our monocular experiments prove that the limen of approach is invariably less than that of recession.

An attempt was made to photograph the images reflected by means of a phacoscope from the anterior and posterior surfaces of the lens when it was accommodated for each of the five standard distances and of the distances given in Table I as just noticeably nearer and farther. It was hoped by this means to determine the radii of curvature of the two surfaces of the lens in each of the fifteen positions of accommodation. From these data, assuming the volume of the lens to remain constant, the determination of the magnitude of its change of diameter for these various positions of accommodation seemed possible. The change of diameter would then indicate the liminal lengthening and shortening of the ciliary muscle. Several difficulties were encountered, however. It was found to be impossible, with any

[1] M. v. Frey: *Untersuchungen über die Sinnes-functionen der menschlichen Haut. Erste Abhaudlung*, pp. 180-188.

available light intensity, to obtain a photograph of the lenticular images. The table of radii of curvature published by Weiss[1] furnished, with interpolations, the data for the anterior surface. Similar data for the posterior surface could not be obtained; though the changes of the latter surface are relatively slight, they can scarcely be ignored. Doubt as to the relative parts played by the straight and annular fibres of the ciliary muscle seemed likely to vitiate our results. Moreover, uncertainty as to the area of the lenticular surface affected by the change of curvature made accurate calculation impossible, and the plan was finally abandoned.

The essential features of our conclusions regarding the perception of relative distance in the monocular experiments may be summarized as follows:

(1) Both the approach and the recession of the fixation-object can be perceived.

(2) These changes of distance are perceived from the corresponding changes of accommodation.

(3) Muscular sensations of accommodation constitute the sense-basis of the perception both of approach and recession.

V. Theory.

When we attempt to bring our results into relation with one or other of the modern theories of psychological space, we must, of course, recognize that these theories are much broader in scope than any single investigation can be. A theory of space must pronounce upon many questions which our problem leaves untouched. Yet it may with justice be maintained that the results of an experimental enquiry—however circumscribed its province—cannot but contribute to our knowledge of the general topic of which it forms a part. Hence it is probable that the conclusions reached in the present study may aid us in adjudicating the relative merits of the rival theories of space,—particularly since it has been concerned with the question upon which the rivals are most at variance.

It is in dealing with the phenomena of relative localization in binocular vision that Nativism has been most successful. The presence of a pair of retinas furnishes a natural basis for the assumption of a paired arrangement of retinal points. From this naturally follows the assumption that retinal disparity and double-images constitute the criteria of relative depth. The theory so far is plausible and alluring; its simplicity of conception and clear envisagement of the process of localization are strong points in its favor. Yet the ultimate criterion of the worth of any scientific theory must be its ability to account for all the facts which it seeks to systematize. And it cannot

[1] O. Weiss: *Tabelle der zur Accommodation auf verschiedenen Entfernungen nöthigen Linsenwölbungen.* *Pflüger's Archiv*, XXVIII, 1902, p. 91.

be denied that however creditably Hering's theory may have acquitted itself as regards the binocular estimation of relative distance, its defects become apparent as soon as it passes beyond this narrow field. Its account of the binocular estimation of absolute distance, and its explanation of the phenomena both of absolute and of relative localization in monocular vision, must be rejected. Moreover, its failure to co-ordinate the phenomena of monocular, with those of binocular vision, casts suspicion upon the whole theory.

The Nativistic theory, whose conception of the process of binocular localization is outlined above, accounts only for the estimation of relative distance. The magnitude of retinal disparity is measured by reference to the retinal center; this central point of reference, is, in terms of the distance of the object imaged upon it, not a fixed but a variable quantity,—since the distance of the point of fixation changes with every change of convergence. Hence it follows that the disparity criterion can furnish only relative depth-values. These values are expressed in terms of the momentary position of convergence, and contribute to a localization relative to the momentary fixation-point. Further than this, a purely retinal theory cannot go. Attempts have been made, however, by Hering and by Hillebrand, to eke out this limitation by a supplementary hypothesis, which we shall later consider.

It is difficult to see how double-images and retinal disparity can furnish an unequivocal criterion of change of distance. Double-images arise, not only when the second fixation-point is nearer, but also when it is farther than the first,—the only difference being the presence of crossed disparity in the former, of uncrossed disparity in the latter case. Hence the assumption that double-images constitute an unequivocal criterion of change of distance, is tantamount to the assumption that crossed disparity can be distinguished from uncrossed, even when their magnitudes have diminished almost to the vanishing point. Experiments with Hering's falling ball apparatus have established a differential limen of about $\frac{1}{50}$. The difference of retinal disparity which is here assumed to be distinguished, approximates to an infinitesimal quantity. Yet Hering's theory asserts not only that these minute differences were detected, but also that there was in every case a consciousness of the kind of disparity present.

Laboratory experiments have frequently shown that observers of normal sensitivity to changes of depth have no immediate knowledge of the kind of disparity operative in a given instance, even when the double-images are manifestly present in considerable degree. The nature of the disparity can be discovered only indirectly, by closure of the one eye and observation of the surviving images with the other. We are not un-

mindful of the familiar phenomena of stereoscopic vision; but we fail to find that Hering's bold statement of the presence of disparity furnishes a satisfactory explanation of the facts in question. The tacit assumption of a retinal capacity, for which experiment gives no warrant, is an insecure foundation upon which to build a theory.

Attention has already been called to the fact that double-images were not consciously present in our binocular experiments. Moreover, it was frequently demonstrated that their intentional production rendered estimation impossible.

The apparent impossibility of distinguishing the double-images occasioned by a farther, from those occasioned by a nearer object, together with the inefficiency of double-images in our own experiments, leads us to reject Hering's criterion as inadequate to the task which it is called upon to perform.

Nor is this the only objection to Hering's conception. The impossibility of finding in the single retina a psychophysical substrate analogous to that posited as ths essential condition of binocular localization, has necessitated the introduction of an extraneous depth-factor. Monocular localization in depth is held to be a function of the 'conscious impulse of will' through which changes of accommodation are made.[1] Monocular and binocular localization are thus differentiated, in that different sense-data and different mental processes are assumed in the two cases. Changes of distance are *seen* in binocular vision; in monocular vision they are in some way discerned through the mediating influence of will.

Here again Hering's assumption is given an unqualified denial by our results. The judgments of our observers followed no less immediately upon the exposure in the monocular than in the binocular experiments. No observer was able to discover a difference in kind between the mental processes involved. We grant, of course, that the levelling effect of time may have modified the processes in question. But that, even after the lapse of ages, two such essentially different processes should have become identical for introspection is scarcely possible. It seems incredible that observers trained in introspection should, in hundreds of trials, invariably fail to detect a difference between a purely sensational process, and a process which is anything but sensational in character.

A further objection to the will criterion assumed by Hering and Hillebrand, is the difficulty of giving it a definite con-

[1] Hering brings forward the principle of coincidence of attention with regard, to account for the localization of the point of fixation; but he identifies the function of attention with that of will (*Raumsinn*, pp. 534 ff.). Hillebrand works out this concept in greater detail and posits a conscious impulse of will as the essential factor (*Zeitschrift*, VII, p. 147).

scious value. Unreasonable as it is to suppose that change of accommodation is ordinarily accomplished by voluntary movement, the matter becomes even more arbitrary when we have to assume that the amount and kind of impulse of will are given us in immediate experience. Just how we become conscious of these minute gradations of will-impulse remains a mystery. Muscular sensations of accommodation would furnish the most natural explanation; but that route is barred, inasmuch as it was the denial of the existence of such sensations that necessitated the impossible hypothesis of conscious impulses of will. Unless we concede the validity of the discarded theory of innervation-feelings, Hering is as far as ever from a satisfactory solution of the problem,—and this concession he can scarcely hope to obtain.

Our examination of Hering's theory has revealed the following defects:[1]

1. It is based upon an assumed retinal capacity which does not exist.

2. Its appeal to the influence of will makes a term do duty for an explanation.

3. It makes an unnatural breach between the phenomena of monocular and of binocular vision.

Our conclusions agree in the main with those of Wundt and Arrer. Upon only a single point—the relative significance of accommodation and convergence in monocular vision—do we take issue with these writers. We have found reason to believe that accommodation is the determining factor in monocular vision, while convergence appears to gain the upper hand in binocular vision. The existence of sensations of accommodation and convergence, is an assumption without which our results cannot be explained. It is true that these sensations received uniform introspective confirmation only in the case of a single observer. But all observers bear occasional witness to their presence. And it is of the essence of Wundt's theory of psychological space as a synthetic function, that the sense-factors involved should, except under the most favorable experimental conditions of analysis, disappear from separate view.

[1] It may perhaps be of interest to learn that the writer began the experimental investigation with a decided leaning toward the theory of Hering. Its conception of the binocular arrangement of retinal points appealed to him as offering a satisfactory psychophysical substrate for the estimation of depth. Hillebrand's apparatus seemed, as it seems even yet, to offer the most advantageous features for an experimental investigation of the problem. Moreover, the criticisms of Wundt and of Arrer seemed, and still seem, to be in several cases unjust. The writer's change of view has been brought about chiefly by the results and introspections of his observers, but also by a more critical examination of the work published by Hering and Hillebrand.